440. Simulation and implementation of a piezoelectric sensor for harmonic in-situ strain monitoring

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Abstract. To monitor the strain in a multilayer steel/adhesive/ceramic beam structure, a 9-µm-thick piezoelectric PVDF film is inserted in the adhesive joint. Two 2D finite element models of the structure with and without the film were developed using a sub-structuring procedure to reduce computational time and to refine the mesh in the thickness of the film. The models provide the harmonic displacement of the beam and the voltage across the film which is related to the strain. A prototype of the analyzed structure has been developed as well. Simulation and experimental analysis was performed and obtained results were compared. It was demonstrated that the influence of the presence of the film on the stress distribution is negligible, thus the implementation of an embedded PVDF film is a well-suited technique to monitor the strain transfer in a bonded assembly.

Keywords: piezoelectric film, Finite Element modeling, in-situ sensor

1. Introduction

Dynamic behavior of multilayered structures depends on the material properties and on the structural frame. The interfaces between layers are the transfer spots of mechanical charges, mechanical over-stress adaptations. The negligible thickness of the adhesive, that bounds the surfaces, could be the source of important energy dissipation in the structure.

A lot of research works deals with the interlayer mechanical dissipation, damage control and damping of multi-material flexible structures using piezoelectric materials as sensors and actuators. They can be either surface bonded or embedded into composite structures.

For example, Chen and Wang [1] demonstrate the feasibility of using the Polyvinylidene-fluoride film (PVDF) fixed on the surface of a cantilever beam as the sensor for structural modal testing. In [2], Sinha and Mujumdar use PVDF films bonded on the surface of a beam for active vibration control and for estimation of a strain transmissibility factor through experiments and finite element simulations.

Embedded sensors have been investigated as well. For example, to examine the dynamic effects of interface stresses and to measure interface energy dissipation in a polymer composite cantilever beam, Agbossou and al. [3] insert a thin layer of piezoelectric material at the interface of composite plies. In the same way, Akitegetse and al. [4] use embedded PVDF strips to measure ice adhesion strength on an aluminium beam.

Our study considers a cantilever beam composed of steel on which a ceramic plate is bonded. The global objective of the work is to implement a method for numerical simulation of the multi-layer steel/adhesive/ceramic structure under dynamical loads, in order to study the strain transfer from one layer to another. To validate the simulation, the beam is fabricated with a thin piezoelectric film inserted inside the adhesive. Using this method, it is expected to optimize the geometric parameters of the structure and to choose the mechanical properties of materials with a real saving of time.

In the first section, the simulation model is described with emphasis on a substructuring procedure, which yields a finer mesh of the adhesive for accurate simulation of piezoelectric film. Then, the experimental setup and the fabricated PVDF-based beam are presented. The experimental results concerning the dynamic response of the actual beam are compared with simulations and discussed.

2. Finite element modeling of the multilayer beam

2.1 Geometrical parameters and materials properties

The studied structure, a steel beam on which a ceramic plate is bonded with an adhesive, is modeled using finite element (FE) modeling software ANSYS®. Due to the beam geometry, a 2D model is developed. The loads are applied in the definition plan. The interfaces between the three layers (steel, adhesive and ceramic) are assumed to be perfect.

A piezoelectric film is introduced in the middle of the adhesive as a sensor in order to study the strain transfer through the multilayer beam. The implemented film is a metallized 9-µm-thick bi-axially stretched Polyvinylidene Fluoride (PVDF) film. The advantages of PDVF materials are numerous, e.g. mechanical flexibility, small thickness, low weight, wide bandwidth. Application of PVDF film is particularly well-suited for building of this assembly since its mechanical properties (stiffness matrix, density) are close to those of the adhesive that bonds the steel and the ceramic together (see Table 1). So the insertion of the film in the adhesive should not create additional stresses. This point will be checked.

The geometrical parameters of the model are given in Fig. 1.

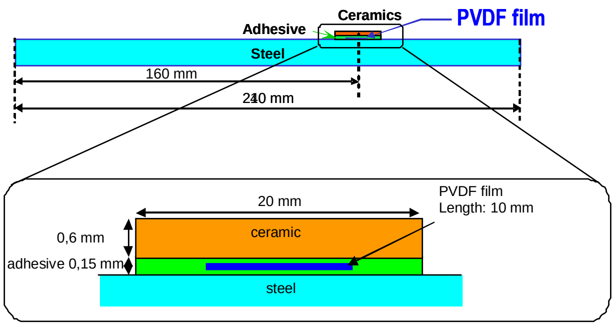


Fig. 1. Model of the fabricated multilayer beam

The three materials (steel, adhesive and ceramic) that composed the beam are supposed to be isotropic, constant and homogeneous. The anisotropic characteristics of PVDF are given thanks to three matrices [5]. The piezoelectric coefficient d_{31} is equal to 7 pC/N. [6].

The properties of all materials are given in Table 1.

Table 1. Mechanical properties of materials

Properties	Steel	Adhesive	Ceramic	PVDF
Density, kg.m^{3}	800	1800	3700	1800
Young's modulus, GPa	210	4	340	[6]
Poisson's ratio	0,3	0,3	0,3	[6]

2.2 Substructuring and meshing

A substructuring procedure is applied in the developed model. The sub-structuring procedure allows a finer mesh in a region of specific interest (superelement), while saving computational time and space memory. It condenses a group of finite elements (the multilayer part of the beam for our study) into one element represented as a matrix. The single matrix element is called a superelement (Figs. 1-2).

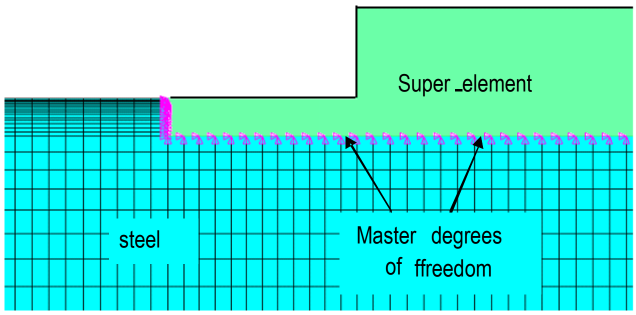


Fig. 2. Model substructuring

The condensation is done by identifying a set of master degrees of freedom, which are used to define the interface between the superelement and the elements of the other part of the structure. Interface nodes between superelement and non-superelement must match the master node locations. Moreover, in order to simulate the interfacial effects correctly, the corresponding areas (piezoelectric films or glue) are meshed with particular care for element sizes (see Fig. 3). The model of the geometrical structure is meshed with plane quadrilateral coupled-field solid elements with two degrees of freedom (DOF) per node (plane displacements), and a third degree of freedom (electric potential) for the PVDF film.

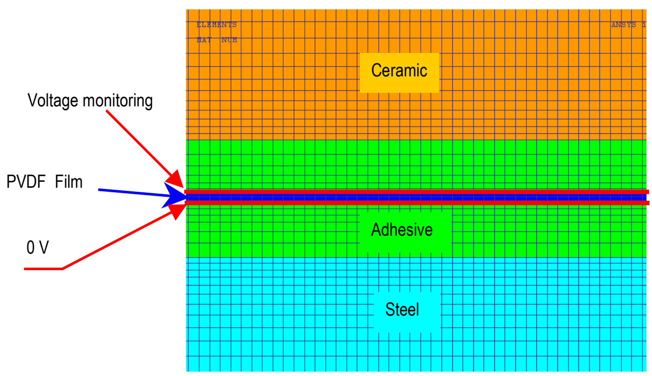


Fig. 3. Zoom of the mesh on the super-element, and boundary conditions applied to the PVDF film

2.3 Boundary conditions and loads

The piezoelectric material, polarized through its thickness, operates in transverse mode. To simulate the metallization of the film, the electrical potential DOF of the nodes representing each face of the piezoelectric film are coupled together. Then, one face of the film is set to 0 V and the other face is used for voltage monitoring (Fig. 3).

Two configurations have been investigated for simulation. The first one is a free configuration where no boundary conditions have been applied. Only a modal analysis is performed. The second one is the clamped-free configuration (see Fig. 4). In this case, the beam is assumed to be perfectly clamped at one end.

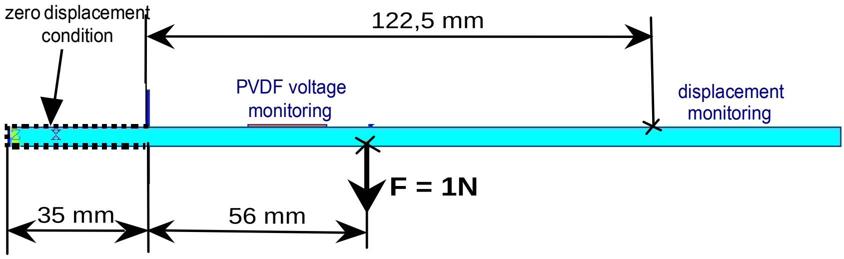


Fig. 4. Boundary conditions and load in the clamped – free configuration

For the harmonic analysis, the force is applied punctually on one node of the model inducing the harmonic excitation in the frequency range around the first two bending modes. The responses of the structure to this forced excitation are recorded by collecting voltage amplitudes of the piezoelectric film and vertical displacements on one point on the surface of the beam.

Finally, a global mechanical damping is introduced in the model for the dynamic analysis using the damping ratio. This damping is necessary to obtain finite amplitudes values in the harmonic analysis.

3. Experimental analysis

3.1 Implementation of the PVDF film

In order to monitor the strain transfer in the beam, we introduced a thin piezoelectric film in the middle of the adhesive.

Three steps have to be done to prepare a PVDF film to be piezoelectrical. Films are first extruded to get a film from the polymer resin. The polymer film is stretched in order to get a preliminary mechanical orientation of the molecular chains. Then an electrical treatment (polarization) is applied to it. Finally, to collect the electrical charges that will appear thanks to the piezoelectric effect, the surfaces have to be metallized with a thin Pt-Au film, about 25 nm in thickness, that is deposited by sputtering on both surfaces.

In the bonding process, the adhesive reticulation is performed at high temperature. The PVDF film was therefore specially developed for our study in order to keep piezoelectric properties after the polymerization. The electrode pattern was specifically designed as well (see Fig. 5). The dimensions of the active area were chosen to be inferior to that of the ceramic to avoid boundary effects. The ceramic is then bonded to the steel with the film inside. A first sample was realized and cut afterwards. Fig. 6 shows its cross-section. As expected, the film lies very close to the middle of the adhesive and runs parallel to the interfaces.

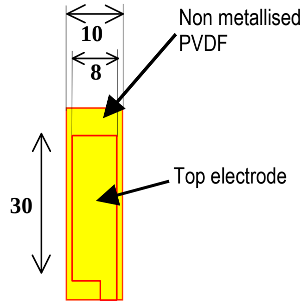


Fig. 5. Electrode pattern of the PVDF film

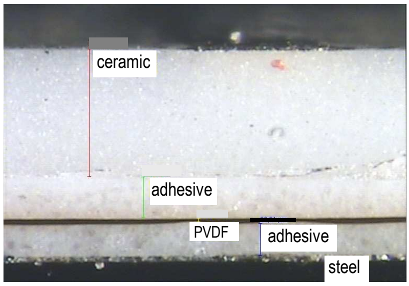
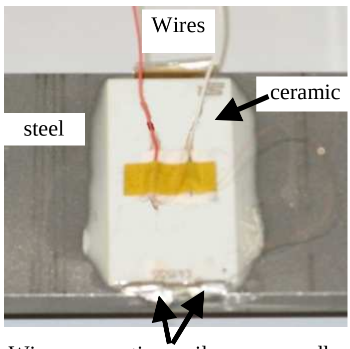


Fig. 6. Cross-section of the multilayer

The final sample with the ceramic, the steel beam and the PVDF film with its electrical connections is illustrated in Fig. 7.



Wires connections: silver epoxy adhesive

Fig. 7. Close-up of the fabricated beam

3.2 Experimental set-up

An experimental setup has been prepared in order to measure the response of cantilever beam, either under free or forced excitations. This setup is composed of a vice and mechanical pieces designed to clamp the beam; an electrodynamic vibrator (LDS V406) to apply a vertical sinusoidal force thanks to vibrating knives in the case of forced excitation; an optical displacement sensor (Micro- Epsilon OptoNCDT 1605) for measuring the vertical displacement of one point at the surface of the studied beam. The dynamic load could be in the range from to 98 N and the acceleration in the range from 0.1 to 9.81 m/s^2. The applied force and the resulting acceleration are monitored through an impedance head (PCB

PIEZOTRONICS 288D01). A picture of the experimental setup is given in Fig. 8. Moreover, in order to improve vibration insulation, the whole structure is mounted on a massive granite base laid on pneumatic feet.

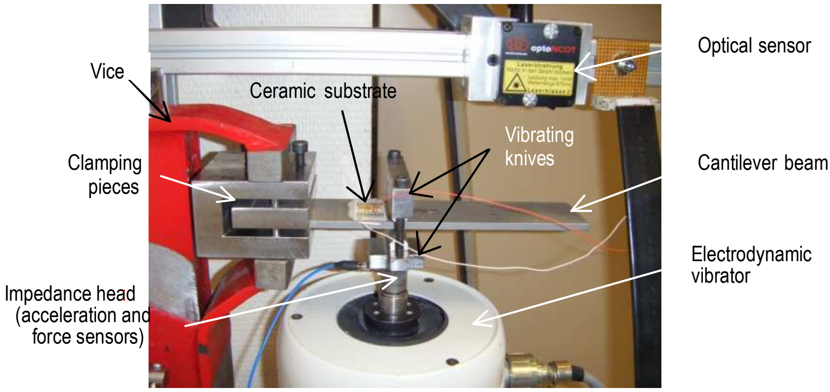


Fig. 8. Experimental setup

3.3 Signal acquisition

The electrodynamic vibrator is connected to a function generator driven by a computer through a power amplifier. Electrical voltage signals issued from the piezoelectric film, the optical sensor, and the impedance head are digitized by a National Instrument acquisition card NT6014. Then, the command of the experiment and the acquisition of the data are controlled by program prepared with LabVIEW®.

To lower the electric impedance of the piezoelectric film, a voltage follower circuit is inserted between the PVDF and the acquisition board (Fig. 9).

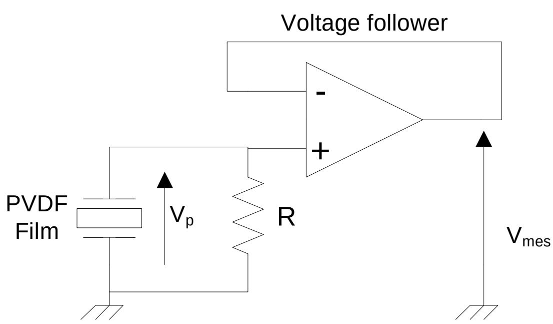


Fig. 9. Piezoelectric film signal conditioner

Since the PVDF film is capacitive in nature, the value of the load resistance has to be high enough to avoid filtering effects at the aimed frequencies. The amplitude of the collected electrical voltage measured by the acquisition board is then related to the PVDF voltage by equation (1).

$$\left|V_{mes}\right| = \frac{RC\omega}{\sqrt{1+R^2C^2\omega^2}}\left|V_p\right| \tag{1}$$

where ω is the angular frequency; R is the load resistance: 2MΩ; C, the capacitance of the film, is calculated with equation (2):

$$C = \frac{\varepsilon_{33}^{S} \cdot S}{e} \tag{2}$$

where S is the active (overlap) area, e is the thickness; and ε_{33}^{S} is the permittivity of the film.

4. Results and discussion

4.1. Influence of the film

The mechanical characteristics of the PVDF film are close to that of the adhesive. Its thickness is fairly thin as well. The effect of the presence of the film is therefore expected to be very weak. However, a dynamic numerical analysis has been performed in which the mechanical characteristics of the PVDF film are replaced with the adhesive ones. The stresses obtained in the adhesive at the first bending resonance frequency of the beam with and without the PVDF are presented in Fig. 10.

It is observed that the Von Misses stresses are very similar in the two cases. A further close-up view at the edge of the film indicates a small difference indicating a slight stress concentration.

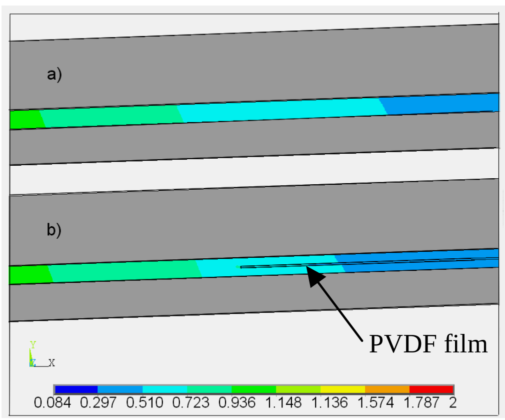


Fig. 10. Detail of Von Misses stresses (MPa) in the adhesive layer of the beam: a) without the PVDF film; b) with the PVDF film

4.2. Modal analysis in the free configuration

In the free-free configuration, the beam is kept horizontally by means of elastic bonds (Fig 11). Pulse excitation is provided with an impact hammer, and the output voltage of the signal conditioner is collected. A FFT is then performed to obtain the natural frequencies of the beam.

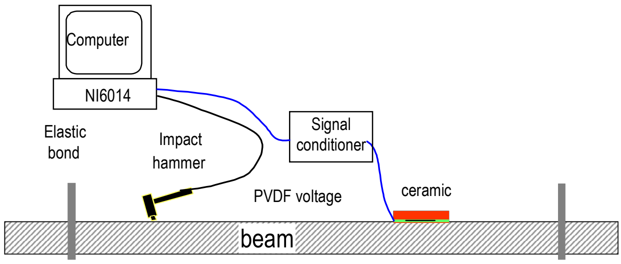


Fig. 11. Scheme of the modal analysis

The two first bending modes frequencies are listed in Table 2, and show a good agreement with the predicted ones.

Table 2. Experimental and numerical bending-mode resonance frequencies in the free - free configuration

	mode 1, Hz	mode 2, Hz
Experimental	625	1715
Simulation	616	1701
Deviation, %	1,4	0,8

4.3 Modal analysis in clamped-free configuration

The scheme of the experiment for studying the harmonic behavior of the beam in the clamped-free configuration is shown in Fig. 12.

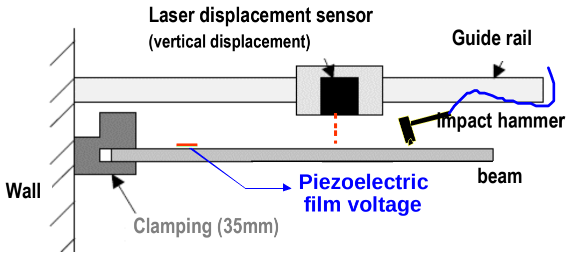


Fig. 12. Scheme of modal analysis experiment in clamped-free configuration

Experimental results reported in Table 3 have been measured using aforementioned devices with a clamping equal to 35 mm.

Table 3. Experimental and numerical bending-mode resonance frequencies in the clamped - free configuration

	mode 1, Hz	mode 2, Hz
Experimental	124	800
Simulation	138	841
Deviation, %	10	5

The agreement between simulated and experimental frequencies is not as good as in the case of free - free configuration. It is concluded that this discrepancy comes from the vice that is not stiff enough to realize a perfect clamping, thus the part of the beam, that is supposed to have a null displacement, can actually vibrate.

4.4 Harmonic analysis of the fabricated beam in clamped- free configuration

As far as experiment is concerned, harmonic analysis of the fabricated beam in the clamped-free configuration is performed with the same conditions as for simulation. The force is applied by means of the vibrator controlled by the frequency generator. The amplitudes of the signals issued, on one hand from the PVDF film (via the electronic conditioner), and on the other hand from the optical sensor, are collected versus the excitation frequency.

As already mentioned, due to the non-perfect clamping, the resonance frequencies do not fit well between experiment and simulation. Thus, in order to be able to validate the damping behavior, the experimental curves were shifted in frequency to match the simulated resonance frequency.

On the other hand, an experimental damping ratio has been calculated in order to calibrate the simulation versus experiment. The following method has been used to obtain the damping ratio from the experiment:

The quality factor Q_m is calculated from the experimental curve of the vertical displacement of the fabricated beam for the first resonance mode (Fig. 13) with:

$$Q_m = \frac{f_r}{\Delta f} \qquad (3)$$

where f_r is the resonant frequency and Δf the bandwidth.
Then, the damping ratio ζ is calculated:

$$\varsigma = \frac{1}{2Q_m}. \qquad (4)$$

Thus, the simulated results reported in Figs. 13-14 use the damping ratio extracted from experimental analysis.

As indicated in Fig. 14, the maximum value of the PVDF voltage is very close to the simulated one. Thereby finite element simulations are validated.

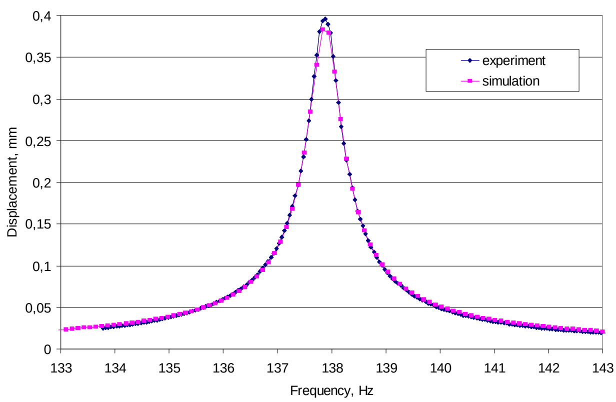


Fig. 13. Harmonic vertical displacement amplitude (first bending mode)

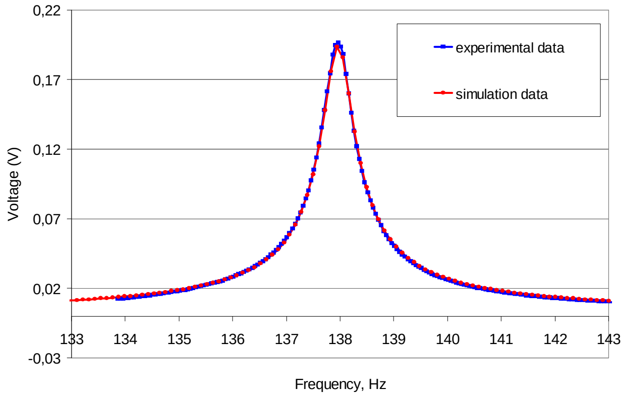


Fig. 14. Harmonic analysis of the voltage collected on the piezoelectric film (first bending mode)

5. Conclusions

The objective of the study was to propose an approach for obtaining a reliable simulation procedure for analysis of the strain transfer through a multilayer beam. A steel beam structure with a ceramic/adhesive assembly has been studied. The numerical model of the three-layer beam, fabricated with piezoelectric thin film integrated in the adhesive, was carried out using a substructuring procedure. Using this model, dynamic simulations were performed: modal analysis in free-free and free-clamped configurations as well as harmonic analysis. It was demonstrated that the presence of the film do not modify the stress distribution in the adhesive. A prototype of a multilayer beam was made with a PVDF thin film. Experimental setup implemented in the laboratory was used to excite bending modes of the fabricated beam structure. The signal obtained from the piezoelectric film has been digitized and conditioned by a dedicated data acquisition system. The evolution of the signal with the frequency was compared to the simulation results. Its amplitude can then be related to the strain in the middle of the adhesive. This measurement enabled validation of the finite element model of the beam, and in particular - the use of the substructuring procedure. It is concluded that the model is helpful for optimization of multilayer structures.

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